Thermal effects in precision systems: Design considerations, modelling, compensation and validation techniques

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Contributed paper

Thermal effects in precision systems: Design considerations, modelling, compensation and validation techniques

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In common high-end precision systems, thermal effects, in general, play a very important role with respect to the final performance of the system. Mainly driven by miniaturization, performance and reliability enhancement, the requirements of these systems have enormously increased over the last few decades. To stimulate exchange of knowledge and cooperation in the precision engineering community a special interest group was initiated by the Euspen. During a meeting in 2006 it turned out that thermal effects occur in many different applications and in all forms. The complexity of the thermal effects and the high impact on the performance of systems motivated the group to organize a conference in 2007. All kinds of applications were mentioned, starting from traditional machine tools up to next-generation lithography tools and analysis tools. The huge diversity of the thermal issues in all kinds of market segments was also very clearly discussed.

A variety of topics have to be dealt with to tackle the variety of problems. Starting with the design itself (Bryan 1990), *design with reduced thermal sensitivity* is a crucial point of departure. Knowledge regarding *inherent stable design*, *controlling conductivity, insulation and shielding* and *thermal design methodologies for non-standard conditions* (e.g. vacuum and cryogenic) is important to be developed. To steer the design in an objective way (Box 2006), *modelling tools and techniques* are necessary (*model reduction*, *model validation* and *error compensation algorithms*) (Evans 1989). *Active control of the thermal state of a system and its environment* are ways to reduce or counteract the amount of thermal distortion. Knowledge about *control algorithms for thermal systems*, *identification of thermal systems* and *thermal actuator design* are required. To apply an active control or to identify or verify a thermal system (Flügge 2006), *measurement methods and experimental techniques* are necessary. To enable this, one needs *fast and accurate temperature sensing*, *accurate temperature calibration methodologies*, *reconstruction techniques of thermal states* and *sensor placement optimization*. In general *accurate data of thermal properties* (e.g. conduction coefficients, interface resistances and radiation emissivity), also under non-standard conditions

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(e.g. vacuum and cryogenic), is indispensable. In the following paragraphs some important features regarding the above-listed topics are given.

1. Design considerations

One of the main design considerations to achieve high accuracy is the use of a separate metrology structure (metrology frame). As, for example shown in Evans (1989), Slocum (1992) and Ruijl (2001), using such a frame means that several optimizations and improvements can be achieved. The use of proper materials (e.g. low-expansion materials like invar or Zerodur), thermal insulation and shielding or even active temperature control are some examples. However, it is important to consider the entire metrology loop. So using, for example, Zerodur scales, as used in some coordinate measuring machines, solves the problem only partly. As indicated by the *thermal effect diagram* (Bryan 1990), the whole metrology chain involves the machine frame, the master (metrology system) and the part. In general, the thermal effects can be tackled by (a) minimizing and controlling the heat flow into the three-element system (frame, master and part), (b) by optimizing the system design in the sense of small sensitivity to thermal disturbance and finally (c) by compensation or correction of the residual errors (e.g. software compensation). The enormous effect that can be reached by shielding is shown in the design of an ultra-precision coordinate measuring machine (Ruijl 2001). In the figure below the effect of aluminium shielding around the metrology frame and the effect of the enclosure around the entire system is shown (figure 1).

The relative fast temperature fluctuations induced by the room are almost completely eliminated by the filtering effect of the shielding and the enclosure. Apart from a transient low-pass filter, the shielding can also act as spatial filter. Deformations of a metrology structure due to bending often give larger

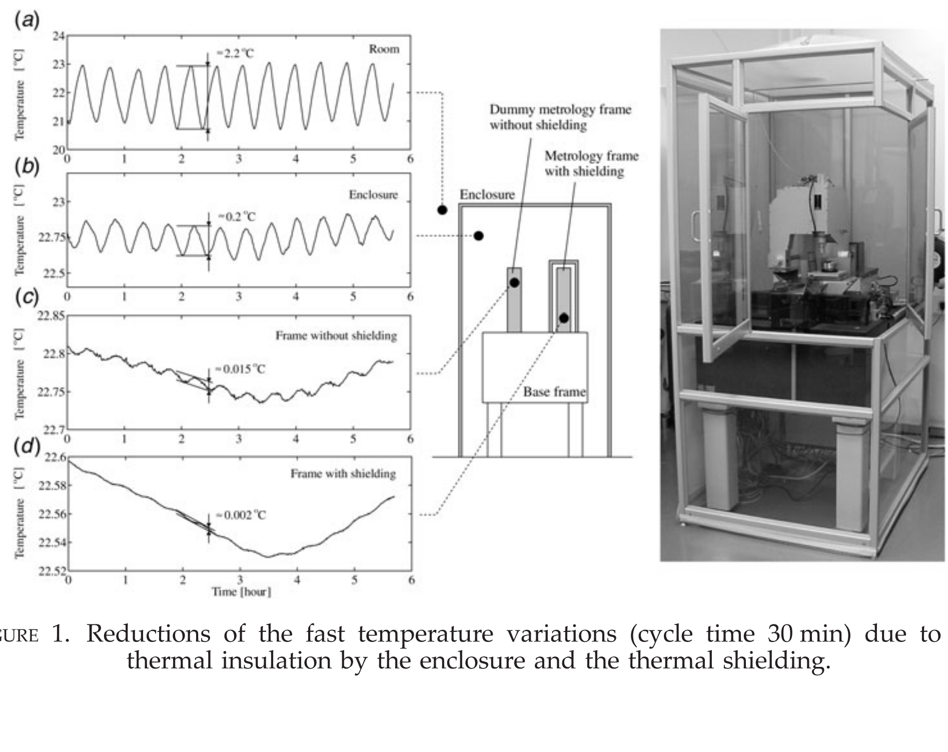

FIGURE 1. Reductions of the fast temperature variations (cycle time 30 min) due to the thermal insulation by the enclosure and the thermal shielding.

deformations than those caused due to simple linear expansion. The high thermal conductivity of the aluminium shielding, as used in the example above, significantly decreases the effects of local heat sources. The use of high conductive materials for the frame itself can also help. For most systems, it is essential to consider the transient thermal behaviour instead of only the steady-state behaviour. In the field of *machine dynamics* and *control theory*, it is very common to consider the behaviour in the frequency domain rather than studying transient responses. It appears that these techniques are very useful for thermal problems as well (Koevoets *et al.* 2007). Knowing that a system operates in a repetitive sequence, optimizing the corresponding periodic transient behaviour of the system is also an interesting approach. Box (Box 2006) shows an example of replacing an expensive invar-welded frame of a lithography tool (wafer stepper) with a more bulky cast aluminium frame. Although the cast aluminium frame has a significantly larger expansion coefficient, it shows better transient performance on the corresponding timescale of the repetitive illumination sequence.

2. Modelling and compensation techniques

Adequate modelling of a system helps significantly in a thorough understanding of the system behaviour. It is essential to manage the design phase to make choices objectively. Making detailed FEM (Finite Element Model) analysis of the component or subcomponents is very common nowadays. Computing power allows solving quite detailed models within acceptable time frames. My personal experience is however, that next to or even better before performing these kinds of detail calculations, the development of a thermal *system model* is essential. Such a model is crucial from a system architectural point of view. Dividing the system into subsystems or modules and describing them finally by lumped masses and thermal resistors is a very effective way to build such a system model. With such a structure the system can also be analysed in the frequency domain very effectively, giving very useful information about the transient behaviour and dominant effects and parameters. With current FEM packages such frequency domain analyses are regrettably still not a trivial job. Simulation packages like Matlab (e.g. Simulink) are very useful to build such thermal system models Sanden vd (2007).

From structural dynamics we know the approach to analyse or describe the system in *mode shapes* (*eigen modes*) and *resonance frequencies* (*eigen frequencies*). In a similar way a thermal system can be described by *thermal-elastic mode shapes* and corresponding *time constants* (Ruijl 2006; Uriarte & Zatarain 2006).

This approach can also be used to reduce complex models to the most essential behaviour (modal model reduction) and to develop thermal compensation models. A comprehensive study was performed by Philips Applied Technologies (e.g. Koevoets *et al.* 2007), see for example figure 2. Besides a modal description other techniques can be used. Based on measurement data, a POD (proper orthogonal decomposition) technique (see section 3) gives very promising results. Other reduction techniques such as Arnoldi reduction are studied as well.

3. Validation techniques

Performing reliable and accurate validation experiments is a crucial step in the development process. Experiments are not only important to quantify the overall final system performance, but should also produce knowledge of the behaviour

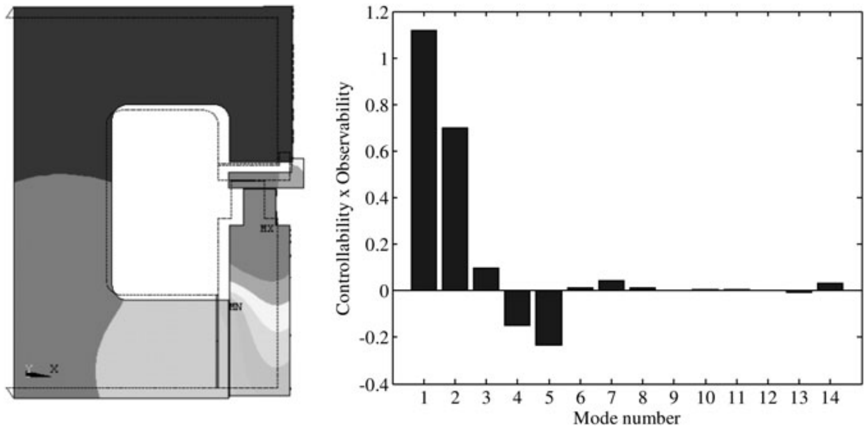

FIGURE 2. Example of a frame analysed by modal techniques. The first mode (thermal-elastic deformation = dashed line, temperature distribution = colour) is shown. The importance of the first 14 modes is shown in the picture on the right.

of the overall system as well as the subsystems. For room temperature applications NTC (Negative Temperature Coefficient sensor) (thermistors) show very good performance and are easy to use. Resolutions below milli-Kelvin are possible. For some applications, thermocouples can be used gaining high resolutions and stability (Flügge 2006).

Performing accurate temperature measurement requires an adequate sensor system. The importance of a proper thermal mounting of the sensor into the system should not be underestimated. Significant errors can occur, even at room temperature, especially if transient disturbances occur.

To validate thermal models or to measure specific thermal properties, transient measurements can produce much more knowledge about the system than steady-state data. Model identification in the frequency domain is very common in structural dynamics and control. For an extensive thermal model of an electron microscope such a method is successfully applied as well. A detailed lump-mass model was made and by means of measuring frequency response functions, important parameters were fitted and the model could be validated. To fit the parameters, dynamic actuation was applied at certain frequencies to achieve good correlation between the actuation distortion and the response of the system. Using the linear behaviour of the thermal problem, the behaviour of the system could be predicted over the entire frequency range of interest. To achieve good correlation becomes difficult at longer timescales as, for example, ambient temperature becomes a significant disturbance source as well. Hence, a proper selection of the actuation source and measurement points is very important.

Another interesting validation technique, which was successfully applied to a frame of a precision system, is based on the POD technique. In this case, one wanted to qualify the thermally induced deformation of the frame in real use cases. An experiment in which only the contribution of the frame was isolated was not possible. Hence, by means of FEM a thermo-elastic model of the structure was made and the relevant deformations of only the structure could be calculated. Next, the structure was equipped with several temperature sensors to measure temperature fields (transient behaviour) during real use cases. A brute force method could be used in which all the temperature fields are analysed by the FEM model to find the corresponding thermo-elastic deformations. However, much faster and with more knowledge, results can be obtained by analysing (reducing) the temperature data first. To reduce the temperature data, a POD was used. Actually, POD finds the entire vector space of the measured temperature distributions. This vector space is given by the POD shapes (temperature distributions). The entire measured transient temperature distribution can accordingly be described by a linear combination of the POD shapes.

4. Summary

As briefly depicted in this paper, the thermal behaviour of systems becomes much more important as performances are increasing and systems become more miniaturized and complex. To tackle the large variety of issues, a variety of topics has to be dealt with: system design principles, modelling tools and techniques, control and correction and compensation algorithms and finally measurement methods and experimental techniques. As already pointed out by Bryan (Bryan 1990), the thermal behaviour of systems can be very complex and has to be understood much better to tackle the challenges ahead. To master the various aspects, as mentioned above, is a huge task and more research in this challenging area is definitely necessary.

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